Modelling of long-term and short-term total ozone variability at Poprad-Gánovce, Slovakia

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A b s t r a c t : The purpose of this study was the construction of the daily total ozone model for Poprad-Gánovce (49.03°N, 20.32°E, 710 m a.s.l.), Slovakia, utilizing the local upper-air measurements performed there since 1961. The model of daily total ozone was created as a sum of two independent models: (1) model of the monthly total ozone values, (2) model of daily total ozone deviations from the monthly average. The long-term variability of the total ozone was modelled using multilinear regression of the monthly total ozone data measured with the Dobson spectrophotometer at the closest observatory Hradec Králové (50.18°N, 15.83°E, 285 m a.s.l.). The differences between the total ozone monthly averages from Hradec Králové and Poprad-Gánovce were negligible (in the range of ±2%), and no systematic bias was detected between both data series during the period of comparison 1993–2004. The content of the ozone-depleting substances concentration in the stratosphere expressed by the equivalent effective stratospheric chlorine (EESC), stratospheric aerosol, index of quasi-biennial oscillations (QBO), index of North Atlantic oscillation (NAO), solar activity expressed by sun spot number (SSN), and upper-air data (height of tropopause for January – February, temperature at 700 hPa level for December and difference between heights of 100 hPa and 250 hPa isobaric levels for the other months) were the parameters tested before inclusion into the monthly total ozone model. Analysis of the Hradec Králové monthly total ozone shows that concentration of ozone-depleting substances in the stratosphere, NAO-index and upper-air parameter belong to the best proxies of the monthly total ozone nearly during the whole year. Aerosols play a significant role in the long-term total ozone variability in December -

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January. Solar activity variations affect the total ozone values in April - July. The QBO index does not affect the total ozone variability significantly during any month, except of February. The comparison of monthly total ozone trends determined from the modelled and measured 1971–2000 time series shows a descending trend of the total ozone during all months. The largest total ozone decrease was detected in April and June, but the most significant linear decrease of total ozone was determined in January and in October. The difference between modelled and measured total ozone trends was below 0.3%. The short-term total column ozone variability was modelled using upper-air proxies only. The error of the final model of daily total ozone was 6%. The coefficient of the determination between the measured and modelled 1993–2004 total ozone was 0.86 at Poprad-Gánovce. The daily total ozone reconstruction has been performed since 1961, but there were large gaps in the upper-air data, and consequently in the modelled daily total ozone in the 60-ties.

Key words: total ozone, Brewer spectrophotometer, Dobson spectrophotometer, upper-air data, NAO-index, QBO-index, SSN-index, EESC, stratospheric aerosol, modelling

1. Introduction

Since the discovery of the polar ozone hole in the 80-ties, the ozone research has been concerned with the study of processes leading to stratospheric ozone depletion. The attention was turned to chemical processes leading to rapid ozone concentration decrease, mainly in the polar region. The relation between the total ozone amount decrease and the increase of the ozone-depleting substances concentration was confirmed by several measurement methods *(WMO, 2004, 1999)*.

It has been shown that stratospheric ozone chemistry, especially in the upper stratosphere, can also be affected by the variability of the solar flux.

Extremely low total ozone values measured after the Mt. Pinatubo volcanic eruption (1991) confirm the role of aerosols in the ozone depletion processes *(Self et al., 1999)*.

Large differences between the north and south polar ozone depletion document the importance of the atmospheric dynamics in the stratospheric ozone depletion in the Northern hemisphere. No significant total ozone depletion has been observed after relatively mild winters when the polar vortex is wake, often disturbed by planetary waves, over north polar latitudes. Contrary to relatively warm stratospheric winters, extremely cool winters have been usually connected with strong polar vortex, and deep spring ozone holes have been observed in polar area of the North hemisphere *(Manney et al., 2005)*.

Variations of the stratospheric ozone concentration related to quasi-biennial oscillations (QBO) were detected not only in tropics, but also over the higher mid-latitudes.

There is a relation between the long-term total ozone and the air temperature variability in the lower stratosphere, but it is not clear how temperature decrease in the lower stratosphere relates to the global lower-troposphere temperature increase *(IPCC, 2001)*.

Appenzeller et al. (2000) were first to note, that relatively large descending total ozone trends detected at Arosa (Switzerland) can be partly explained by long-term changes of the circulation patterns in the North Atlantic Ocean, expressed by the North Atlantic oscillation (NAO) index. It was also detected, that the NAO circulation pattern contributes to total ozone increase, and mitigates total ozone negative trends over the higher latitudes (Iceland). Many other studies (e.g. *Dameris et al., 2003*) have analyzed the effect of different climate teleconnection patterns on the total ozone variability and trends since *Appenzeller et al. (2000). Orsoliny et al. (2003)* analyzed the effect of many teleconnection patterns also with remote centres of action on total ozone measured by the satellite system TOMS (total ozone mapping spectrophotometer) in mid-latitudes (30°N – 70°N). They showed that there is a tight correlation between total ozone values and some quasi-periodic circulation patterns, depending on geographical locality.

Appenzeller et al. (2000), analyzing the Arosa and Reykjavik total ozone data, and *Steinbrecht et al. (1998)* analyzing the February Hohenpeissenberg total ozone, concluded that the quasi-periodic circulation patterns can affect the trends in total ozone time series, while *Hansen and Svenøe (2005)*, analyzing the 65-year long Tromsø (Norway) total ozone measurements, did not confirm the effect of the investigated circulation patterns on total ozone trends. *Metelka et al. (2005)* used the neural networks to analyse total ozone changes in Europe during the period 1957–1999. The chemical depletion effect on total ozone was expressed by a time-dependent variable entering the model. Heights and temperatures of the selected isobaric levels, NAO–index, aerosol optical depth, variability of solar activity expressed as radio flux at wavelength $\lambda = 10.7$ cm were the next proxies. The model results indicated that the main part of the systematic changes of total ozone is connected to the evolution of ozone-depleting substances in the stratosphere.

All the investigated models of monthly total ozone, including different circulation patterns as proxies, manifest a high correlation between the measured and modelled data, and can be used not only for analysis of existing total ozone time series, but also for validation, homogenization and regional reconstruction of total ozone.

The main purpose of this study is to create the total ozone daily average reconstruction model reliable for Poprad-Gánovce, where the total ozone measurements have been performed only since 1993, but the upper-air measurements (important proxies of the total ozone) have been available here since 1961.

As the Poprad-Gánovce the total ozone time series is not long enough to create a regression model reflecting the long-term variability of the total ozone, a regression model of monthly total ozone was built using total ozone measurements from the close observatory Hradec Králové located also in Central Europe, nearly at the same latitude as Poprad-Gánovce.

The first step of modelling the long-term total ozone variability was the analysis of phenomena affecting the long-term variability of total ozone measured by the Dobson spectrophotometer at Hradec Králové *(Vaníček et al., 2003)*.

2. Material and methods

The multilinear regression analysis was applied to create a reconstruction model of the daily total ozone at Poprad-Gánovce. The model contains two independent parts: (1) model of the monthly total ozone values, (2) model of the daily deviations from the monthly average. Important input parameters entering both parts of the reconstruction model were upper-air data measured at Poprad-Gánovce. Homogeneity of upper-air measurements since 1961 has been checked and considered suitable for climatological analyses

(Chmelík, 2000). However, the sounding systems operating in 60-ties did not often reach levels of the middle and upper stratosphere. That is the reason, why 100 hPa isobaric level is the highest used in the model.

The inputs into the second part of the reconstruction model were only the upper-air data (height of selected isobaric levels, differences between selected isobaric levels heights, temperature at chosen isobaric levels) from the day of total ozone measurement and also from the day before it. The problem of short-term total ozone changes modelling is a high degree of autocorrelation of modelled data and also the correlation between input upper-air data *(Pribullová and Chmelík, 2000).* Individual regression equations were constructed for every month.

Only one upper-air parameter (marked as parameter DYN), manifesting the best correlation with the total ozone, entered the model of the monthly total ozone. Temperature of the lower troposphere (at 700 hPa isobaric level), height of the tropopause and temperature at the lower stratosphere, characterized by the difference between the 100 hPa and 250 hPa isobaric level heights, were the tested aerologic parameters for the monthly total ozone model. Except the winter months, temperature of the lower stratosphere has been the best correlating upper-air parameter.

Time series longer than the 11-year total ozone measurements performed at Poprad-Gánovce are needed for building the monthly total ozone model involving the effect of phenomena with longer periodicity (e.g., variability of solar activity, variability related to teleconnection patterns). Total ozone measurements performed at the observatory Hradec Králové by the Dobson spectrophotometer (measurements since 1962) were used for the monthly total ozone model construction. The 1971–2000 data-set was employed for the monthly model construction due to availability of continuous and homogeneous time series of upper-air proxies at Poprad-Gánovce and total ozone data at Hradec Králové. Total ozone measurements with the Brewer spectrophotometer MKIV have been performed at Poprad-Gánovce since August 1993. Both instruments (Dobson spectrophotometer at Hradec Králové and Brewer spectrophotometer at Poprad-Gánovce) have been regularly calibrated. Total ozone data obtained at both observatories were compared during the 1993–2004 time period, when Poprad-Gánovce measurements were available. Absolute differences between daily total ozone measured at Hradec Králové and at Poprad-Gánovce were the largest during January –

Table 1. The lag of QBO- and NAO-indices time series in months, what the highest absolute values of coefficient of determination between monthly total ozone and QBO-index and between monthly total ozone and NAO-index was calculated for 1971–2000 data were elaborated

Month	1	2	3	4	5	6	7	8	9	10	11	12
QBO	-8	-10	-2	-15	-13	-13	-13	0	-6	-16	-20	-20
NAO	-8	-12	-12	-10	-3	-4	-9	-6	-5	-9	-9	-9

March, when the relative difference between both data sets was 5%. The frequency of relative differences less than 5% was in the range of 62–72% during all investigated years. Comparison of monthly total ozone data confirms good agreement between both time series. Relative differences between monthly total ozone values do not exceed 2%. The total ozone measured at Poprad-Gánovce fits well also the TOMS satellite measurement (version 8.0 of TOMS data). Relative differences between monthly averages do not exceed 3% during 1997–2004 period, when the satellite data were available. The largest discrepancy between daily total ozone values was determined in the period October-December (9%). The frequency of low relative differences between ground and satellite data (less than 5%) was in the range of 70–85% at Poprad-Gánovce.

The other input parameters used in the monthly total ozone modelling were similar to those usually applied in multilinear regression analysis of total ozone time series *(WMO, 2004)*.

The ozone depletion was involved in the model through equivalent effective stratospheric chlorine concentration (EESC) in ppbv, calculated for the area of Central and Western Europe using Baseline scenario A1 *(WMO, 1999)*. EESC data extended from 1900 to 2005 can be found the internet site `http://dataservice.eea.eu.int`. The concentration of EESC was expressed as a nearly constant until the year 1960. A linear function represented the increase of EESC since 60-ties until the years 1997–1998, when the maximal content of ozone-depleting substances in the stratosphere was supposed. The descending trend of EESC has been assumed since the peak of the EESC concentration until the present.

The variability of solar activity was parameterized by the sun spot number (SSN). The data source was on the web site of The Solar Influences Data Centre of the Royal Observatory of Belgium. Unsmoothed monthly

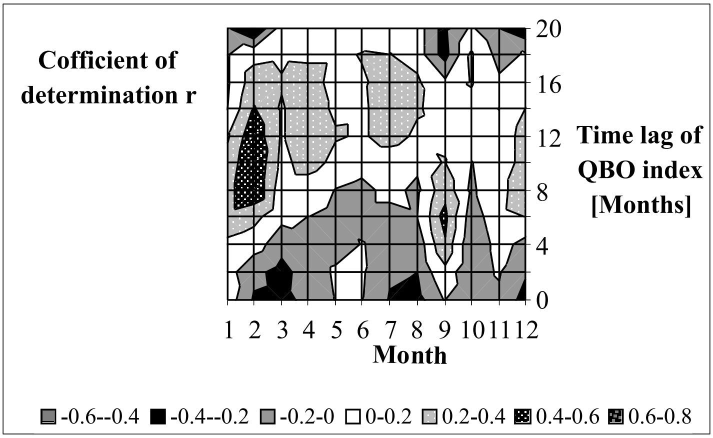

Fig. 1. Coefficient of determination between monthly total ozone at Hradec Králové and QBO-index in 1971–2000 period. The QBO-index was lagged in the aspect of total ozone from 0 to 20 months.

values of SSN-index have been available since 1750.

Atmospheric oscillations were represented by two atmospheric oscillation patterns: the quasi biennial oscillation (QBO) and the North Atlantic oscillation (NAO). As soon as investigated circulation patterns can affect the local values of total ozone with any lag, time series of the QBO- and NAO-index were lagged in the aspect of the total ozone data. The time lag manifesting the best correlation between the investigated circulation pattern and the total ozone was applied to the data.

The QBO was characterized by average velocity of zonal wind at the 30 hPa level at the tropics *(Naukojat, 1986)*. The data source was on the web page of the University of Washington `http:/tao.atmos.washington.edu/data/qbo/`. The QBO-index was lagged to total ozone time series from 0 to 20 months. The lagged QBO-index time series best correlated with the total ozone were used in monthly total ozone model (Table 1). The QBO-oscillation affects the total ozone values at Hradec Králové by positive correlation and also by anticorrelation (Fig. 1). The best positive correlation between monthly total ozone and QBO-index was detected in February, when the QBO-index was between the first three best proxies of monthly total ozone.

The NAO-index represents the monthly average of differences between

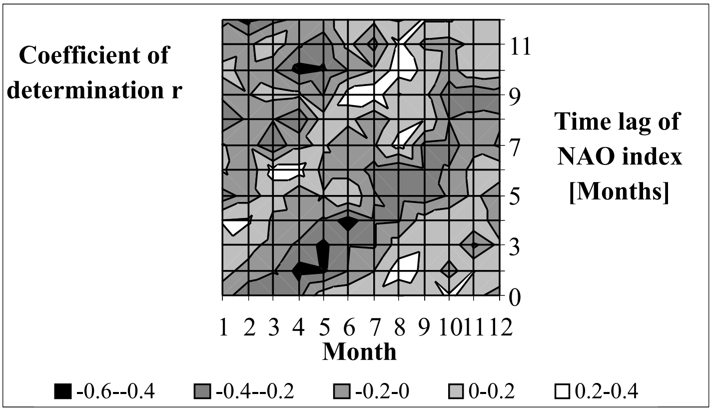

Fig. 2. Coefficient of determination between monthly total ozone at Hradec Králové and NAO-index in 1971–2000 period. The NAO-index was lagged in the aspect of total ozone from 0 to 11 months.

sea level air pressure at Stykkisholmur in Iceland and in Lisbon, normalised to December-March average values and recalculated with respect to 1864–1983 data *(Hurrel, 1995)*. The monthly NAO-index data presented at the web page of Climate Prediction Centre of the National Oceanic and Atmospheric Administration (NOAA) `pc.ncep.noaa.gov/products/precipp/CWlink/pna/nao.s html` were involved in the model. Similarly to the QBO-index, also the NAO-index data were lagged with the aspect of total ozone time series (the tested NAO-index lag was of 0–11 months). Differently lagged NAO-index time series entered the monthly total ozone model equations (Table 1). The highest positive coefficient of determination between the monthly total ozone and NAO-index was detected in July with NAO-index lagged 9 months in the aspect of total ozone time series. The largest negative coefficient of determination (best anticorrelation) between the monthly total ozone and NAO-index was found during all months, except of July, with the time lag of the NAO-index ranging from 4 to 12 months (Fig. 2).

The content of the stratospheric aerosol (model parameter AER) was characterized by an aerosol optical depth for radiation with wavelength 340 nm. Average values calculated for the area 40° – 50° N were found at internet page of the Surface radiation research branch of NOAA `http:/www.srb.noaa.gov/research/aerosol.html`. Increased values of the aerosol optical depth were recorded after huge volcanic eruptions e. g., Mt. El Chicon (1982), Mt. Pinatubo (1991).

Correlation analysis of the data shows that the relation between monthly total ozone and its proxies has a seasonal course (Fig. 3). It was necessary to select the parameters determining the total ozone in every month. In the first step all available proxies of monthly total ozone were ordered descending according to individual correlation coefficient. The significance of every proxy parameter contribution to quality of linear regression was tested using the partial F-test. The input parameters were once again sorted in descending order in accordance with the F-test values. The proxies were one after the other added into the multilinear model. The change of the reduced correlation coefficient after addition of the next parameter was a criterion for intrusion of the parameter into the model. If the reduced correlation coefficient increased after addition of the proxy parameter, the parameter was involved into the model, if it did not, the investigated parameter and all following parameters were not used in the model. The parameters selected as inputs into the model of monthly total ozone are summarized in Table 2.

Table 2. The proxy parameters selected for monthly total ozone multilinear model. The parameters are in descending order in accordance with significance of their contribution to monthly model improvement characterized by partial F-test method. 1971–2000 Hradec Králové total ozone data was elaborated. Legend to model parameters is explained in text

Input parameter order	1	2	3	4	5	6
Month						
1	AER	NAO	EESC	QBO	DYN	SSN
2	NAO	DYN	QBO	AER	EESC	SSN
3	DYN	EESC	NAO	SSN		
4	EESC	NAO	SSN	QBO	AER	DYN
5	DYN	SSN	EESC	NAO	QBO	AER
6	EESC	SSN	DYN	NAO	QBO	AER
7	DYN	NAO	EESC	QBO	SSN	
8	DYN	EESC	NAO	QBO	AER	SSN
9	DYN	NAO	EESC			
10	DYN	EESC	NAO	AER	QBO	SSN
11	DYN	AER	NAO	QBO	EESC	
12	AER	NAO	DYN	QBO	SSN	

The order of input data reflects the contribution of every input parameter to total correlation between modelled and measured data. The statistical analysis shows, that the model incorporated also parameters manifesting low significance of their contribution to linear model quality determined by the F-test values. The reduced coefficient of determination, however, slightly increased after inclusion of these parameters into the model. It is probably more due to the dependence of the reduced correlation coefficient on the number of model parameters, than due to a real contribution of the noted input parameters to the model improvement. The trend analysis of modelled and measured total ozone time series was performed.
The reconstruction of the Poprad-Gánovce daily total ozone time series has been performed since 1961.

3. Results and discussion

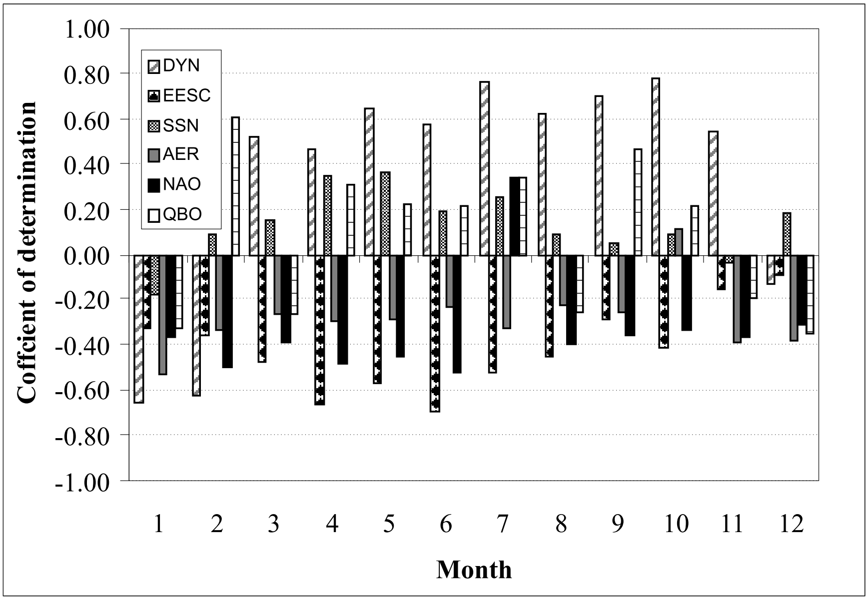

Fig. 3. Coefficient of determination between monthly total ozone at Hradec Králové and its proxy parameters used in monthly total ozone model determined from 1971–2000 data. Explanation of legend can be found in text.

The reconstruction model of the daily total ozone at Poprad-Gánovce O_{3DAY} was created as a sum of monthly average of total ozone O_{3AVG} model and model of deviations of daily total ozone from monthly average ΔO_3. The modelled daily total ozone was calculated using the following formula:

$$O_{3DAY} = O_{3AVG} + \Delta O_3. \qquad (1)$$

3.1. Model of monthly total ozone

The number, sort, and order of the input parameters entering the model of monthly total ozone differ from month to month. The coefficient of determination between measured and modelled monthly total ozone ranged from 0.63 to 0.86 (Table 3) at Hradec Králové. The December and March were months with the lowest coefficient of determination ($r < 0.70$). Decrease of correlation during the winter months probably relates to selection of the upper-air parameters. It is known, that during winter months the total ozone correlates better with higher standard pressure level characteristics (10 hPa – 30 hPa) *(Pribullová and Chmelík, 2000)*, than those involved in the model. Decrease of correlation between measured and modelled monthly total ozone during winter months can also relate to selection of monthly total ozone proxies – probably also other teleconnection patterns can affect variability of total ozone during this months. The root mean square (RMS) error of the monthly total ozone model was below 3% from May to November, which is comparable with differences between Poprad-Gánovce ground and TOMS satellite data. Increase of RMS error was detected during December – April, when the RMS error increased to values of 3.1% – 4.8% (Table 3). The coefficient of determination between the measured and modelled monthly total ozone r was of 0.96 and RMS error of 2.9% at Hradec Králové for the period 1971–2000 (Fig. 4A). The coefficient of determination between the measured and modelled monthly total ozone r was 0.93 and RMS error of 3.4% at Poprad-Gánovce for the period 1993–2004 (Fig. 4B). The analysis of the modelled Hradec Králové monthly total ozone shows that concentration of ozone-depleting substances in the stratosphere affects the total ozone not only in April and June, when the largest total ozone decrease was detected. The EESC was between the first three best correlated parameters determining the monthly total ozone during the whole

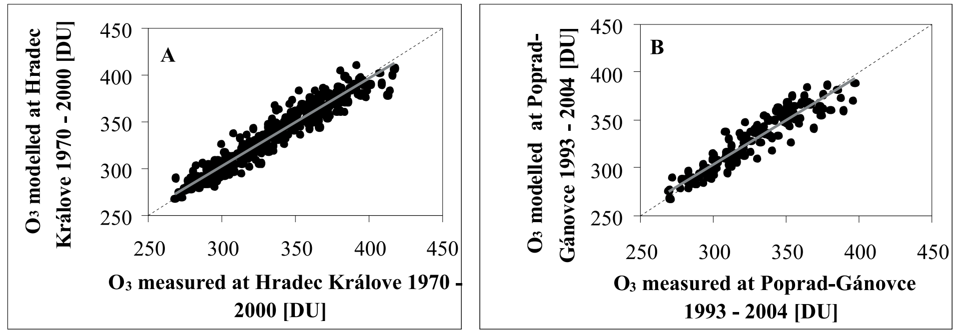

Fig. 4 A-B. Measured monthly total ozone as a function of modelled monthly total ozone at Hradec Králové during period 1971 – 2004 (4A) and at Poprad-Gánovce during period 1993 – 2004 (4B) expressed by linear functions (grey line).

Table 3. The coefficient of determination r between measured and modelled monthly total ozone at Hradec Králové (1971 – 2000), RMS error of the model, linear trends of modelled O_{3mod} and measured O_{3meas} monthly total ozone in %/decade and differences between linear trends of modelled and measured monthly total ozone. Statistically significant trends of total ozone calculated at significance level $\alpha = 0.25$ are marked by grey bold letters, statistically significant trends of total ozone calculated at significance level $\alpha = 0.05$ are marked by black bold letters. The first three best monthly total ozone proxies are for each month in the last three rows. If their linear trends are statistically significant at the significance level $\alpha = 0.05$, parameters are marked by bold letters and the linear trend calculated in %/decade is shown in brackets.

Month	1	2	3	4	5	6	7	8	9	10	11	12
r	0.85	0.81	0.66	0.83	0.81	0.84	0.86	0.73	0.80	0.86	0.70	0.63
RMS [%]	4.2	4.8	4.8	3.1	2.7	2.3	1.6	2.3	2.4	2.4	2.6	4.0
Trend O_{3meas} [%/decade]	-2.2	-1.6	-2.1	-2.6	-1.9	-2.5	-1.4	-1.2	-0.4	-1.5	-0.3	-0.4
Trend O_{3mod} [%/decade]	-2.2	-1.7	-2.3	-2.8	-1.9	-2.4	-1.3	-1.1	-0.7	-1.6	-0.5	-0.1
Trend difference O_{3meas} - O_{3mod} [%/decade]	0	0.1	0.2	0.2	0	-0.1	-0.1	-0.1	0.3	0.1	0.2	-0.3
Parameter 1 (trend [%/decade])	AER	NAO (64)	DYN	EESC (91)	DYN (-2.0)	EESC (91)	DYN (-0.4)	DYN	DYN	DYN	DYN	AER
Parameter 2 (trend [%/decade])	NAO	DYN	EESC (91)	NAO (111)	SSN	SSN	NAO	EESC (91)	NAO	EESC (91)	AER	NAO (161)
Parameter 3 (trend [%/decade])	EESC (91)	QBO	NAO	SSN	EESC (91)	DYN	EESC (91)	NAO (169)	EESC (91)	NAO (103)	NAO (169)	DYN

year except November, December and February. Except January and April, the upper-air parameters belong to the best total ozone proxies. Inclusion of the NAO index into the model improves its quality during the whole year, except April and May. The monthly total ozone is determined mainly by the atmospheric oscillations (NAO, QBO) and also by ozone-depleting substances concentration in stratosphere in February (the QBO effect on the total ozone was found to be more significant during February only).

The solar activity variations were between the three best proxies of monthly total ozone in period April–June.

Aerosols determine the long-term total ozone variability from November to January.

To detect possible differences in long-term variability of measured and modelled monthly total ozone, both 1971–2000 data series dependence on the time was expressed by linear function. For all months and both modelled and measured data, descending lines fitted the total ozone dependence on the time (Table 3).

The steepest decreasing trend of total ozone of -2.5%/decade and -2.6%/ decade was detected analysing the measured data in April and June, respectively. During these months, the parameter EESC determined the total ozone values. The trend of modelled total ozone was of -2.8%/decade in April. The differences between linear trends calculated from modelled and measured data were of range 0.0–0.3%/decade. The largest difference of 0.3%/decade was detected in December and September. Statistical significance of trends was tested using the method of variance analysis. The hypothesis of nonzero slope of linear function expressing the monthly total ozone dependence on time was tested. The values of linear trend obtained from statistically significant regressions at the significance level $\alpha = 0.25$ are depicted by bold grey letters in Table 3. Trends calculated at the significance level $\alpha = 0.05$ were detected for modelled total ozone in two months only – January and October (bold black letters in Table 3). Except of the total ozone trends, also linear trends of its first three best proxies were calculated and analyzed with respect to their statistical significance (Table 3). Monthly total ozone proxies manifesting statistically significant linear dependence on the time are marked by thick letters, trends determined at significance level $\alpha = 0.05$ are in brackets in the Table 3. Increasing statistically significant linear trend of EESC (91%/decade) was equal for all months. Trend analysis of other monthly ozone proxies shows, that statistically significant linear increasing trend of NAO-index can affect the totals ozone trend in period February – April and also from August to December. Anticorrelation between monthly total ozone and NAO-index was detected during these months. This indicates an idea, that prevailing positive phase of the NAO-index observed during the 90-ties *(IPCC, 2001)* can relate to the enlargement of the total ozone decrease in Central Europe. But on the other hand, no significant negative trend of the total ozone was detected in August and November, when the largest ascending trend of the NAO-index was detected. Statistically significant decrease of lower stratospheric temperature (expressed via upper-air parameter DYN) was determined in May and July. It is not clear, how the ozone concentration decrease in the lower stratosphere contributes to negative temperature trends observed there, and how long-term changes of climate (green-house effect) affect the radiation balance and consequently temperatures in the lower stratosphere. Neither the aerosol content in the stratosphere (in spite of increasing trend detected in winter months), nor the solar activity variations manifest a statistically significant linear trend during the investigated period at Hradec Králové.

3.2. Model of daily total ozone deviations from the monthly average

The assumption that short-term changes of the total ozone relate to the variability of atmospheric dynamics was used only by modelling the daily total ozone deviations from monthly average. Four upper-air characteristics (temperature at 700 hPa isobaric level, height of 250 hPa isobaric level, differences between the 100 and 200 hPa isobaric level heights and temperature difference between 100 and 250 hPa isobaric levels) determining temperature of lower stratosphere and troposphere entered the model. As daily total ozone manifests strong autocorrelation, the same upper-air data obtained on the day of total ozone measurement and also on the day before it were used as model input parameters. Finally eight upper-air parameters were incorporated into the model. Model equations were created separately for every month, but equal number and sort of input parameters were used for every month. Linear relation between the upper-air data and the deviation of daily total ozone from its monthly average was assumed. The model was constructed applying 1993–2000 upper-air and total ozone data measured at Poprad-Gánovce.

The model RMS error ranged from 10 DU in August to 28 DU in January (Table 4). The coefficient of determination between measured and modelled values ranged from 0.69 to 0.83 (Table 4). It confirms good agreement between the signs of modelled and observed deviations of daily total ozone from monthly average.

3.3. Model of daily total ozone

The modelled daily total ozone was obtained as the sum of the monthly total ozone and a deviation of daily total ozone from its monthly average. Finally, 11 - 14 input parameters were required for daily total ozone modelling. While model of total ozone deviations from its monthly average was based on local upper-air data only, the model of total ozone monthly averages was constructed using Hradec Králové total ozone, global characteristics of solar activity and ozone-depleting substances content in the stratosphere, regional teleconnection pattern indices and stratospheric aerosol characteristic, and local upper-air data. The final model of daily total ozone was tested on 1993–2004 Poprad-Gánovce data. The differences between measured an modelled daily total ozone were determined for daily ozone modelled using both measured and modelled monthly total ozone, separately. The RMS error of the daily total ozone model was 5.4% (17 DU) and the coefficient of determination r was 0.90 when measured monthly total ozone entered the model. But the model of daily total ozone was not significantly deteriorated after using the modelled monthly total ozone (RMS = 20 DU or 6.1%, r = 0.86).

Table 4. The coefficient of determination $\boldsymbol{r}$ between modelled and measured deviations of daily total ozone from monthly average and RMS error of model of daily total ozone deviations from monthly average in Dobson units (DU) calculated from 1993–2000 Poprad-Gánovce data.

Month	1	2	3	4	5	6	7	8	9	10	11	12
r	0.73	0.83	0.82	0.74	0.76	0.79	0.82	0.73	0.81	0.69	0.71	0.69
RMS [DU]	28	23	21	21	13	12	10	10	11	11	20	23

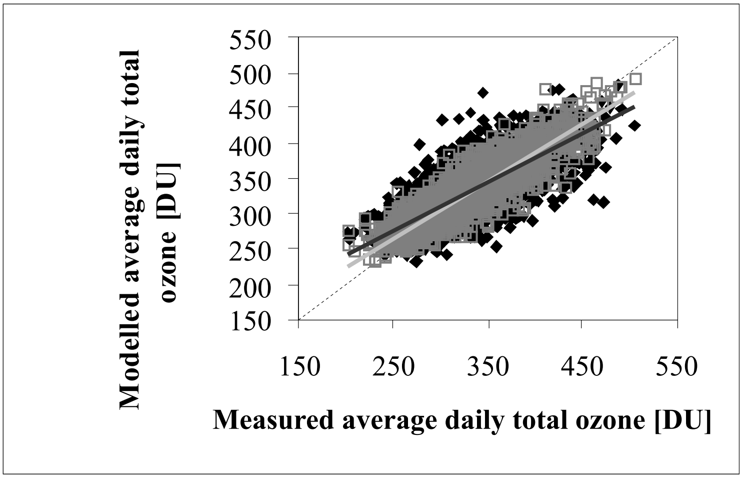

Fig. 5. Measured daily total ozone as a function of modelled total ozone for model with usage of monthly total ozone measured at Hradec Králové (grey symbols) and for modelled monthly total ozone (black symbols) at Poprad-Gánovce in period 1993–2004 together with linear fits of both data groups.

The modelled daily total ozone using the measured and the modelled average monthly total ozone as a function of measured daily total ozone is in Fig. 5. Linear regression lines of these scatter-plots are also depicted in this Figure. Lower scattering of data and regression line closer to ideal case, when modelled daily total ozone is equal to measured values, can be seen on scatter-plot of daily total ozone modelled using measured monthly total ozone as an input. Underestimation of the highest values of daily total ozone and overestimation of extremely low daily total ozone is more significant for daily total ozone calculated using modelled monthly total ozone data. The model error varies in annual course. Table 5 shows RMS errors of daily total ozone for every month.

Deterioration of the model can be seen during the winter months (Fig. 6), when RMS error of the model increased to values of 7.6–9.8% .

The RMS error values are below 5% from May to October. Lower differences were found between modelled and measured daily total ozone than between satellite and ground-based measurements of daily total ozone at

Table 5. *RMS* error of daily total ozone model in % calculated from 1993 – 2004 Poprad-Gánovce data

Month	1	2	3	4	5	6	7	8	9	10	11	12
RMS [%]	9.8	8.7	7.3	6.7	4.1	4.9	4.7	4.2	4.6	5.5	7.6	8.0

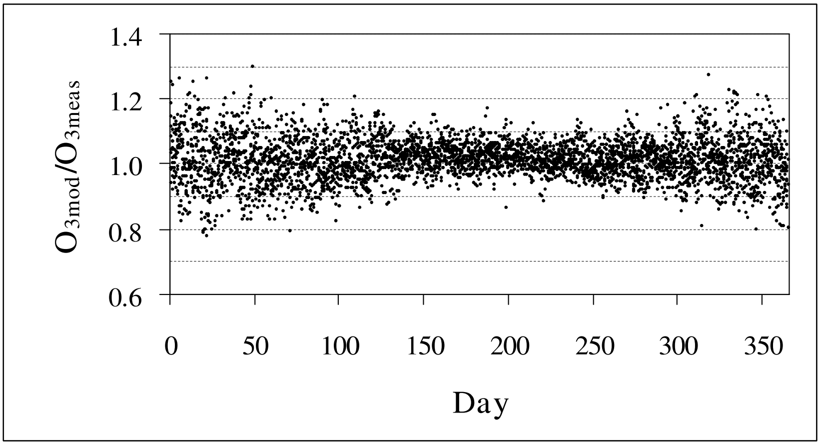

Fig. 6. Annual course of the ratio between modelled and measured daily total ozone at Poprad-Gánovce in period 1993–2004.

Poprad-Gánovce from October to December. Error of the daily total ozone model is by nearly 2% larger than the differences between Poprad-Gánovce and Hradec Králové daily ozone (average difference between daily total ozone at Hradec Králové and Poprad-Gánovce was of 4.6% in period 1993–2004) and also larger than the differences between the ground-based and the satellite total ozone measurements at Poprad-Gánovce.

4. Conclusions

The purpose of this study was to construct the daily total ozone model for Poprad-Gánovce utilizing the local upper-air measurements performed there since 1961. The model of daily total ozone was created as a sum of two independent models: (1) model of the monthly total ozone values, (2) model of the daily total ozone deviations from the monthly average. Long-term variability of the total ozone was modelled using multilinear regression analysis of monthly total ozone data measured by the Dobson spectrophotometer at the closest observatory Hradec Králové. Differences between the total ozone monthly averages from Hradec Králové and Poprad-Gánovce were negligible (in the range of ±2%) and no systematic bias was detected between both data series during the period of comparison 1993–2004. The 1970–2000 total ozone data from Hradec Králové were utilized for the monthly total ozone modelling. The linear increase of the ozone-depleting substances concentration in the stratosphere, stratospheric aerosol content, index of quasi-biennial oscillations, index of North Atlantic oscillation, solar activity expressed via sun spot number and Poprad-Gánovce upper-air parameters (height of tropopause for January – February, temperature at 700 hPa level for December and difference between heights of 100 hPa level and 250 hPa level for the other months) were the parameters tested before inclusion in the monthly total ozone model. Correlation analysis and partial F-test were applied to select the parameters that significantly affected the model quality. The analysis of the 1971–2000 Hradec Králové monthly total ozone shows, that in spite of usage of the upper-air proxies measured at Poprad-Gánovce, upper-air parameter affects the monthly total ozone at Hradec Králové significantly during all months, except January and April. Total ozone depletion term was between the three best proxies of monthly total ozone, except November, December and February. The NAO-index also frequently belongs to the best monthly total ozone proxies. Exceptions are months April and June, when the largest total ozone depletion was detected. The variability of solar activity affects the monthly total ozone more significantly during summer months April – June and does not play an important role in the monthly total ozone variability during the rest of the year. Aerosols affect total monthly total ozone variability significantly in winter. The QBO-index was found between first three best significant proxies only in February.

The analysis of linear trends of both measured and modelled monthly total ozone shows that there are not large differences between trends determined from measured and modelled data. The largest differences between trends do not exceed 0.3%/decade. Both the modelled and measured total ozone decreasing trend was detected during all months. The linear regressions of total ozone as a function of time were significant at significance level $\alpha = 0.25$ from January to July and during October. Trends and their statistical significance were determined also for the first three best monthly total ozone proxies. Statistically significant linear increase of the NAO-index (at the significance level $\alpha = 0.05$) with time was determined in February, April, and August and from October to December. As monthly total ozone anticorrelates with NAO-index lagged in the aspect of total ozone by different number of months, there is possible effect of NAO circulation pattern on long-term changes of total ozone. Upper air parameters expressed as difference between height of 100 hPa and 250 hPa isobaric levels (proportional to lower stratosphere temperature) also significantly decreased during investigated 1970–2000 period. It is not clear from this study how this trend relates to total ozone depletion and how the effect of tropospheric green-house phenomena contributes to the lower stratospheric temperature decrease.

The significant (at significance level $\alpha = 0.05$) descending trend of total ozone detected in October is interesting, which can relate to the NAO-index long-term variability and also to the ozone-depleting substances concentration increase in the stratosphere. It is also worth to note, that the decreasing trend of the monthly total ozone was determined more by the NAO and QBO teleconnection patterns and aerosols in February, than by the long-term variability of the ozone-depleting substances.

The short-term total column ozone variability was modelled using the aerologic proxies only. High degree of correlation was reached between modelled and observed deviations of daily total ozone from monthly average.

The error of final model of daily total ozone was 6.1%. Coefficient of determination between measured and modelled 1993–2004 total ozone was 0.86. The use of measured monthly total ozone instead of modelled one improves the daily model RMS error to the value of 5.4% (r = 0.90). During summer months, the model error is comparable to differences between daily total ozone at Hradec Králové and at Poprad-Gánovce. From October to December the model error is less than differences between satellite and ground-based measurements at Poprad-Gánovce. The largest discrepancy between measured and modelled daily total ozone occurred in winter. During winter months, the selection of different upper-air proxy parameter (higher standard pressure level heights) can probably improve the model quality, or the additional proxies (other teleconnection patterns) are needed for daily total ozone modelling. Probably also usage of regional, not local, indices of the NAO teleconnection pattern can contribute to the model improvement. The daily total ozone reconstruction has been performed since 1961, but there are large gaps in the aerologic data and also in the modelled daily total ozone in the 60-ties. The series of reconstructed daily total ozone is available at the authors of this publication. The analysis of total ozone at Poprad-Gánovce using reanalyzed homogeneous and continuous upper-air data will be carried out in the future.

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